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THE ELEMENTAL COMPOSITION OF QUIET TIME LOW ENERGY COSMIC RAYS MEASURED ON THE VOYAGER SPACECRAFT

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ABSTRACT

We have used the large collecting area of the Voyager telescopes to obtain greatly improved statistics on the elemental composition of quiet time low energy cosmic rays above ∿3 MeV/nuc. Three quiet time periods totaling 115 days between August, 1977 and February, 1978 are used. These quiet times are further subdivided into still quieter periods totaling 47 days. At low energies, the most prominent feature is the anomalous component which has a peak intensity at ∿6 MeV/nuc. It is observed most prominently for N, O and Ne nuclei, but we believe it has been identified for the first time for C, Mg and Si nuclei as well at a much lower intensity level. This component undergoes strong solar modulation effects, and also for O nuclei at least, shows 27 day enhancements associated with enhanced intensities of ∿0.5 MeV protons.

1. Introduction

It is now apparent that several separate populations of cosmic rays are present at low energies in interplanetary space even at times when direct solar accelerated cosmic rays are not obviously present. At energies lower than 100 MeV/nuc, the intensity of the galactic cosmic ray component, with a well known charge composition, is observed to decrease ∿E. At ∿20-30 MeV/nuc the intensity of several nuclei, helium, nitrogen and oxygen at least, begins to increase. This new component, with a spectral exponent ∿-2.0, has been termed anomalous because its composition is totaly unlike the galactic cosmic rays at higher energies or the solar cosmic rays (see review by Gloeckler, 1975 for further details of this component). At still lower energies, <10 MeV/nuc, the spectrum of this anomalous component peaks and seems to merge into still another quiet time component with possibly a steeper spectrum. The details of the transition between these components have been reported by Klecker et al., 1977. But the picture is far from complete with regard to the charge composition and energy spectral details of these low energy populations. In this paper we use the combined data from eight (8) low energy telescopes, with a total collecting area ∿3.5 stcm^2, on the Voyager 1 and 2 spacecraft to examine these low energy nuclei with greatly improved statistics. The results suggest the presence of features in the spectra of several other elements that resemble the features observed for the so called anomalous oxygen. In addition, we examine the transition to a still lower energy component which is strongly correlated with interplanetary disturbance conditions.

2. The Instrumentation and Data Periods

Each Voyager spacecraft carries four (4) identical LET telescopes positioned along orthogonal axes. An outline drawing of one of these telescopes is shown in Figure 1. Each telescope has a geometrical factor ∿0.44 stcm^2. For element and energy identification the dE/dx x E technique was used. The energy range was divided into five (5) intervals for each charge. The first interval consisted of particles stopping in the L2 counters, the next four intervals consisted of particles stopping in L3. The energy intervals were defined from energy loss calcu-

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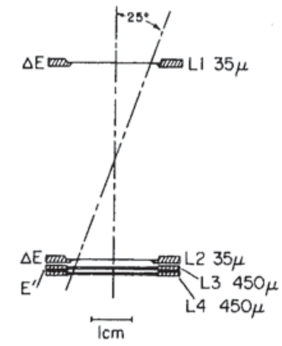

Figure 1. Outline drawing of LET telescope on Voyager spacecraft.

lations in the individual silicon detectors whose mean thicknesses were carefully determined. The energy range covered was 3.6-17.2 MeV/nuc for oxygen nuclei with corresponding energies for the equivalent range of other nuclei.

The Voyager 1 and 2 spacecraft were launched in August and September, 1977 and proceeded together towards the outer solar system. Small differences in radial and aximuthal positions are not of importance in the analysis here, and the data from the two spacecraft are combined. There was considerable solar and interplanetary activity during the period after launch but we were able to define several quiet time periods for data analysis. The first level of quiet times was defined by requiring the three (3) day average oxygen intensity between 3.6-6.5 MeV/nuc to be at a background level $<4\times10^{-5}$ particles/cm^2-ster-sec-MeV/nuc. A second and more stringent quiet time which was a subset of the first intervals was then defined by requiring the three (3) day average helium intensity between 1.8-3.0 MeV/nuc to be at a background level $<5\times10^{-4}$ particles/cm^2-ster-sec-MeV/nuc. The days included in the quiet time analysis are shown in Table I.

TABLE I
Quiet Time Periods
Inclusive Days (1977-78)

	I	II	III	Total
Level 1	275-325	335-2	14-44	115 days
Level 2	294-304	340-360	29-43	47 days

This time period covered the first 160 days after the Voyager launches and at the end of the period, the two spacecraft were approximately 2.3 AU from the sun.

3. Experimental Results

In Figure 2, we show the charge composition of events stopping in the L3 counter (3 dimensional charge analysis) for the combined Level 1 quiet time periods (energy range 4.8-17.2 MeV/nuc for O nuclei). The anomalous abundance of N, O and Ne nuclei relative to the known galactic abundance of these charges is clearly evident. The events for several nuclei such as Be, B, Na and Al most likely represent the low energy part of the galactic spectrum. The events for charges such as C, Mg, Si and Fe are a possible combination of several components as will be discussed later. The complexity of the origin of these charges is reflected by the fact that this overall composition looks neither galactic or solar or even a simple combination of the two sources.

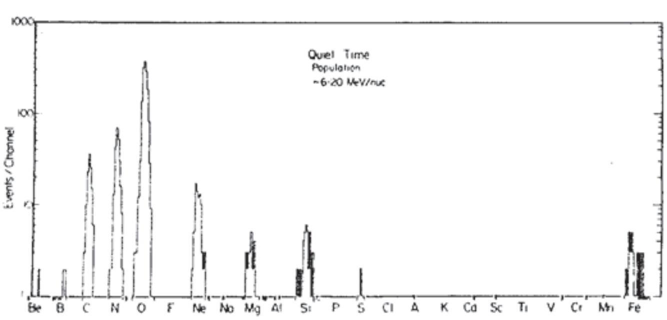

Figure 2. Charge histogram of quiet time data.

We next constructed energy spectra for the most abundant of these charges for the Level 1 quiet time data. These spectra are shown in Figures 3 and 4. In these figures, the expected spectra of the modulated galactic component are shown as a dashed line for each charge normalized to the well known abundances measured above 100 MeV/nuc (Webber, et al., 1972, Garcia Munoz et al., 1977). The upturn in the spectra of the N and O nuclei is clearly observable. Also, the upturn in the spectrum of Ne is now clearly seen - thus establishing firmly the anomalous nature of this charge. In these Figures the line labeled 2.0 has a spectral index of -2.0 and is used principally to guide the eye.

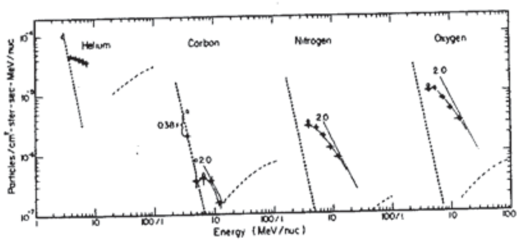

Figure 3. Energy spectra of quiet time He, C, N and O nuclei. (See text for description of lines and symbols in this Figure and Figure 4.)

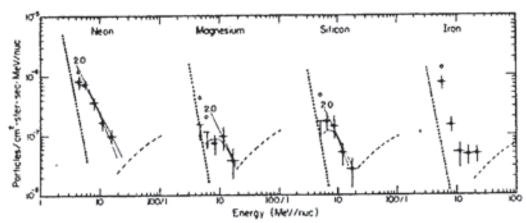

Figure 4. As above for Ne, Mg, Si and Fe nuclei.

For the other charges the low energy spectrum is not as simply interpreted. All charges show a rapid increase in intensity in the lowest energy channels. We therefore, have considered the data from quiet time period 2. This data is shown as the solid points at low energies -only when the intensities differ from the quiet time 1 period which is then shown as an open circle. The low energy quiet time component has now been reduced significantly for some nuclei, although for N, O and Ne which have an enhanced abundance already, only small effects are observed in the lowest energy channel. For the lowest energy C nuclei, the intensity is now 0.38 of its value in quiet time interval 1. In fact, as this low energy steep spectrum component is removed, a bump still remains for C, Mg and Si nuclei which looks very similar to the much more prominent features for N, O and Ne nuclei. In an attempt to specify the picture at low energies more clearly, we have assumed that two components exist. For illustrative purposes only, we show for each charge a low energy component as specified by the period 2 low energy spectrum of C nuclei and with a charge abundance like the average observed for solar cosmic rays by Cook et al., 1979. This component is shown for all charges, but is not significant for N, O or Ne because of their enhanced abundance at these energies. The remaining component at intermediate energies for C, Mg and Si appears to have a spectrum similar to that for the anomalous N, O or Ne nuclei. In effect we suggest that an anomalous component of C, Mg and Si exists, undetected previously. The reality of this component is evident from the data in Table II where it is obvious that at ∿10 MeV the observed abundance is neither galactic or solar or any simple combination thereof. The combination of better statistics, and the wide energy

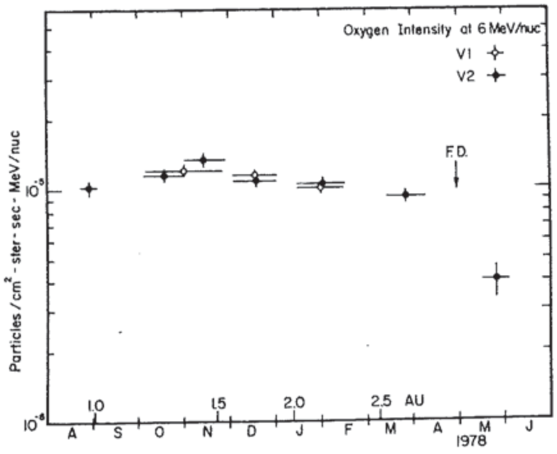

Figure 5. Quiet time intensity of anomalous O nuclei measured on Voyager I and II.

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scale has allowed us to observe this component for the first time sandwiched between the galactic component at higher energies, and a steeper low energy component.

The situation for Fe nuclei is not clear. Only a small change in the lowest energy channel is apparent when the stricter criteria are applied. The low energy component is much more pronounced for Fe. It appears that a possible additional anomalous component for Fe may exist with a peak at ∿15 MeV/nuc, but to verify this will require additional spectral details at higher energies.

Table II summarizes the data on the relative abundance and spectral characteristics of the anomalous component. We can observe no significant dependence of the location of the energy of the intensity peak with charge, nor can we discern any clear differences in spectral shape of these components from the ratios at different energies.

It is obvious that this result broadens the scope of our understanding of this quiet time cosmic ray population -and in particular, the anomalous component. In an effort to further understand this component, we have examined some features of the temporal variation of its most abundant constituent, O nuclei. Figure 5 shows the O nuclei intensity at the spectral peak as a function of time after launch for Voyager 1 and 2 . At the end of this time period, these spacecraft were ∿3.5 AU from the sun. Other quiet time observations (Webber et al., 1975) have indicated that the gradient of these nuclei is ∿+20%/AU in the inner solar system, but overall the intensity measured on Voyager decreased after launch, indicating that temporal variations were dominent. Especially note the effects of the large Forbush decrease that occurred when the Voyager spacecraft were at 3.0 AU from the sun, and which decreased the intensity of the O nuclei by a factor 2.3±0.3.

TABLE II

Relative Abundance
of Anomalous Component

Charge	Energy of Peak (MeV)	Abundance at Peak	Abundance at 10 MeV
C	7.0±1.5	4±1	∿4
N	∿4.0	25±2	21±2
O	5.3±0.5	100	100
Ne	∿5.0	8±1.2	∿4
Mg	∿10	0.9±0.3	∿1.7
Si	8.0±2.0	1.5±0.4	∿2.0
Fe	?	?	<1.0

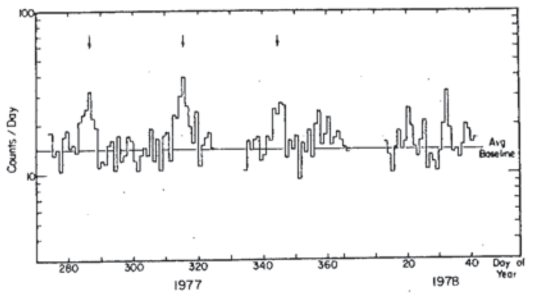

Figure 6. Daily average number of O nuclei counts.

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The temporal variation of the quiet time O nuclei is examined on a daily basis in Figure 6. The data refers to 3.6-17.2 MeV/nuc and is corrected to a constant live time -hence the non-integral numbers of counts. There is evidence for a co-rotating 27 day enhancement in the O nuclei intensity. This is identified by peaks on days 287,316 and 345 of year 1977. At later times this co-rotating structure is not apparent, but non-statistical enhancements in the O intensity may still be occurring (eg day 33 of 1978).

4. Discussion and Interpretation of the Data

We identify a component which appears at intermediate energies and has a peak intensity for all charges at ∿6 MeV/nuc. It is observed most prominently for N, O and Ne nuclei, but we believe it has been identified for the first time for C, Mg and Si nuclei as well. This component is identified with the previously known anomalous components of N and O. The generally accepted explanation for this component is due to Fisk et al., 1974. This theory rests on the fact that atoms such as He, N, O, Ne and A have first ionization potentials greater than hydrogen and may thus exist in interstellar space as neutral atoms. As neutrals, they can penetrate to the vicinity of the sun, be ionized by solar UV and then partake in the streaming motion of the solar wind, being eventually accelerated in the outer solar system. Strictly speaking, according to this theory, only atoms with ionization potentials >13.6 eV could partake in this process, and the observation of He, N, O and Ne enhancements was strong support of this. Our observation that other charges apparently partake in this acceleration, although with a significantly weaker source function suggests that this picture, if correct, is incomplete. Possibly a small percentage of the other atoms exist as neutrals in interstellar space and we are seeing a selective process at work depending on the exact ionization fraction of the atoms in question. Or perhaps, partially ionized solar wind atoms of the correct charge to mass ratio also participate in the acceleration model. The Fisk et al., model predicts that the ions from an interstellar source should be singly charged, but it has not yet been possible to unambiguously determine this charge state and so determine their origin. Other charge states would be possible if some of these particles had a solar wind origin.

The general time variations that we and others have observed are consistent with solar modulation effects on a low energy component. However, if these particles are singly charged they have a high rigidity and will therefore behave somewhat differently. We hope to examine the time variations reported here more fully. It should be possible by studying these variations as a function of energy for different charges and by simultaneously determining the radial gradients to deduce the charge state of these particles. This should be possible with Voyager (and IMP) data.

The observation of 27 day recurring enhancements of the anomalous O nuclei is a new phenomenon. A 27 day periodicity has been reported for Helium nuclei, however (Garcia Munoz et al., 1977) and it is possible that the two phenomena are related. The Oxygen enhancements correspond to an increase ∿ a factor of 2 above the already enhanced baseline O nuclei intensity. These enhancements are associated with co-rotating increases in the low energy ($\gtrsim$0.5 MeV) proton intensity, although no increase in any of the other charges is detectable (eg the lowest energy carbon channel) at these times above 3.6 MeV/nuc.

Finally, we should briefly discuss the very low energy component. A similar component has been identified by Klecker et al., 1977, but they consider it to have a much flatter spectrum (γ=-2). Our data for C, Mg and Si require a much steeper spectrum, which incidently is not inconsistent with the data of Klecker et al. One possibility is that these particles represent residual low level co-rotating streams that are not individually identifiable. These streams have a composition similar to the composition of solar cosmic rays (Gloeckler et al., 1979), and therefore, except for Fe, would fit our data. Gloeckler et al., find that the heavy nuclei in these streams all appear to have the same exponential spectra, which again would be consistent with our data, and to have steep equivalent energy spectra above a few MeV/nuc.

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